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The DURIP funds have been spent on several ultra high vacuum systems important to the advance of high power microwave generation. Novel oxide cathodes have been fabricated in our vacuum-arc plasma deposition chamber that produce high emission densities of 20 A/cm^2 and display low work functions of only 1.6eV, wihich were made possible by the low vacuum pressures produced by the equipment purchased under the DURIP grant. Two Cusp electron guns have been delivered to UC Davis by Northrop Grumman. These state-of-the-art electron gunds will be employed to drive UC Davis' efficient high harmonic gyrotrons and peniotrons.

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Ultra-High Vacuum Systems for Gigawatt HPM Generation

Final Report for the Defense University Research Instrumentation Program

AFOSR DURIP Grant F49620-97-1-0145
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Ultra-High Vacuum Systems for Gigawatt HPM Generation

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Ultra-High Vacuum Systems for Gigawatt HPM Generation

1.0 Overview

The DURIP funds have been well spent on several ultra high vacuum systems important to the advance of high power microwave generation. Novel oxide cathodes have been fabricated in our vacuum-arc plasma deposition chamber that produce high emission densities of 20 A/cm^2 and display low work functions of only 1.6 eV, which were made possible by the low vacuum pressures produced by the pumps and equipment purchased under the DURIP grant. A new mechanism for RF breakdown has been identified that could not have occurred without the high vacuum produced by the DURIP grant equipment. An innovative high power modular klystron manufactured by low-cost micro-fabrication techniques is being developed whose required high vacuum will be produced by the vacuum equipment purchased under this DURIP grant. Two Cusp electron guns have been delivered to UC Davis by Northrop Grumman. These state-of-the-art electron guns will be employed to drive UC Davis' efficient high harmonic gyrotrons and peniotrons. In addition, the DURIP funds have been employed to upgrade the Phillips Lab Gemini pulser with ceramic seals so that it can be operated with a high vacuum to suppress the RF breakdown that currently occurs.

2.0 Impact of Instrumentation on Progress of Primary Contract

2.1 Oxide Cathodes

We have been successful in our initial experiments in a basic research program focussed on the physics issues related to the development of high emission, long lifetime oxide cathodes. ATRI students Ryan Umstattd and Tao Pi have been the primary investigators, working under the supervision of Prof. Luhmann of UCD and Drs. G. Caryotakis, G. Scheitrum, and R. Phillips of Stanford in a MURI UCD/Stanford collaboration. Oxide cathodes are much more economical to produce than dispenser cathodes and can supply the electron beam current necessary for advanced vacuum electronics. The objective of this project is to understand the underlying physics issues leading to the development of the process for both manufacturing and testing high performance oxide cathodes which can reliably emit 100 A/cm^2 with moderate lifetimes and lower current density at longer lifetimes. The significant accomplishments achieved in this project were enabled by the instrumentation purchased under this DURIP grant.

Mr. Umstattd has successfully fabricated several BaO-SrO oxide cathodes in his vacuum-arc-plasma-deposition chamber which were measured to be capable of pulsed current densities of 20 A/cm^2 and possess work functions equal to 1.6 eV. Because of Barium's propensity to adsorb water, it was found necessary to first completely remove all of the water from the vessel. Stable production of Barium and Strontium plasmas was obtained after a separate trigger cap was added to the plasma gun. The cathodes with a coating thickness of 1-1.5 um were made by firing ~1000 shots. Mr. Umstattd has proven that vacuum arc plasma deposition is an innovative method for making high emission oxide cathodes without the introduction of adhesives or binders that are commonly used which may later poison the cathode. Captain Ryan Umstattd recently filed his Ph.D. thesis on his research and development of vacuum-arc-plasma-deposited oxide cathodes and is now on assignment at the Air Force Research Laboratory.

Ms. Pi is responsible for evaluating the electron emission properties of the oxide cathodes. Employing her ultra-high-vacuum analysis chamber, two CPI carbonate oxide cathodes have been activated and tested. Unfortunately, their emission was only ~20 mA/cm^2, probably because they had been exposed to air for several months before testing. Auger analysis found a considerable amount of Carbon on the surfaces, which indicates that they had been poisoned. In other work, the activation anode is now differentially pumped by a separate Turbo Pump to ensure that binders and other potential poisoning materials do not enter the main chamber during cathode activation. A heating package has also been added to the anode to bake out the water vapor before testing the cathodes and a Kelvin Probe to measure the cathode's work function has been tested and calibrated on a piece of aluminum. The analysis chamber was sent to Thermionics to add new ports for mounting the new AUGER/XPS/SEM system, which will be used to study the surface chemistry of the cathodes.

The Oxide Cathode project has greatly benefited from the instrumentation ordered under the DURIP grant. It is essential to maintain a high vacuum in both test stands, especially the cathode analysis chamber. The DURIP grant allowed us to achieve these low pressure levels and to purchase the needed experimental control electronics. The equipment purchased included a) a transistor switch with cooling fins for the discharge capacitor bank, b) an electrostatic plasma probe to measure the plasma properties of the discharge, c) fused Silica viewports to be able to visually look into the chamber, d) rebuilt vacuum pumps and equipment from Duniway Stockroom and some new vacuum equipment from Varian, e) a load lock door for 6" OD conflat flange to enable the use of movable mechanical arms and probes, f) a Millennia MME 166 computer to control the experiments and collect and analyze data, g) a spectrometer for measuring the properties of the system,. h) a Sputter etching system to keep the vacuum-arc-plasma-deposition chamber clean, i) a digital delay generator to control the timing of the discharges for the vacuum-arc, and i) fabrication work through Thermionics and MDC Vacuum to add new diagnostic ports to both chambers.

2.2 RF Breakdown

The RF breakdown program is focused on isolating and experimentally investigating the fundamental mechanisms related to breakdown. Some of the mechanisms analyzed include multipactor, grain boundaries, microparticle contamination, coatings, and pulse duration. ATRI student Lisa Laurent is the lead investigator of this project on high gradient RF breakdown studies under the supervision of Drs. G. Caryotakis, R. Phillips, and G. Scheitrum of Stanford and Prof. Luhmann of UC Davis in a MURI UCD/Stanford collaboration. The objective of this project is to study the mechanisms for RF breakdown in order to suppress it and thereby increase the output power capability of HPM sources. Ms. Laurent has obtained the important result that adsorbed gas on grain boundaries can induce RF breakdown. One test platform used for studying RF breakdown has been the X-band resonant ring at Stanford capable of supplying up to 300 MW of traveling wave power for a pulse duration of 1.5 microseconds at a pulse repetition rate of 60 Hz. A TM_{02} cavity with removable noses and a diagnostic arc detector is used to study the various stages of breakdown. Two sets of noses were analyzed, S1 and S2. They both underwent the same processing except that S2 spent 9 hours in a vacuum furnace at 800^{o}C. Set S1 had considerable RF breakdown picked up by the arc detector at the RF field level of 150 MV/m and showed evidence later of many breakdown sites along the grain boundaries. Set S2 did not have any RF breakdown picked up by the arc detector at the same power level and did not show any evidence of breakdown sites along the grain boundaries. The repeatability of these results was verified by testing a new set of copper noses under the same conditions. The conclusion is that RF breakdown can be induced by gas from the grain boundaries and that vacuum firing will outgas these boundaries. A pure crystal conductor which does not have grain boundaries is clearly desirable as the raw material.

In other work on the project, the effects of microparticle contamination on rf breakdown was analyzed. A set of cavity noses were SEM mapped for micron size particles prior to rf testing, and repeatedly SEM analyzed at various power levels. The results of this study revealed that submicron size particles did not contribute significantly to rf breakdown. In addition, a second test platform with an X-band 50 MW klystron directly coupled to the breakdown cavity through a 3-dB magic tee is being utilized to study the effects of residual gas and pulsewidth on breakdown. The breakdown structure is isolated from the klystron by two TE_{11} windows allowing the test structure to be baked out prior to rf testing to achieve ultra-high vacuum conditions. An extractor gauge mounted directly to the cavity enables the pressure to be monitored from 10^{-12} Torr to 10^{-7} Torr. The initial pressure in the cavity after bakeout was found to be $5x10^{-11}$ Torr. This was found to be an order of magnitude higher than experimental testing without bakeout. In addition, preliminary results have shown that breakdown is inversely proportional to the one-third power of the pulse duration ($t^{-1/3}$). The pulsewidth study was performed from 80-1500 ns with field gradients ranging from over 550 MV/m at 80 ns to 250 MV/m at 1500 ns. Also noted in these tests, was thermal deformation of the high field surface area for two sets of noses that were processed above 550 MV/m at 80 ns. This was observed prior to and separate from arcing.

The RF Breakdown project has been significantly aided by the equipment purchased under the DURIP grant. The equipment purchased included a) a residual gas analyzer to monitor the gas species inside the breakdown cavity, b) a VCR/monitor to visually monitor breakdown, and c) a peak power sensor head for a HP peak power analyzer to monitor the power into and out of the cavity.

2.3 High Power W-Band Modular Klystron

ATRI students Liqun Song and Jeff Li are involved in a research program to develop a revolutionary W-band micro-fabricated modular klystron under the direction of Drs. G. Caryotakis, A. Vlieks, and G. Scheitrum of SLAC. The objective is to obtain a compact, modular, high power 94 GHz amplifier. The modular klystron approach consists of using klystrons of very low perveance (0.075 microperveance), high voltage PPM-focused electron beams, with several tubes fabricated on a common planar substrate and operated in parallel. This results in a favorable form factor, good efficiency and the possibility of paralleling several modules for an arbitrary amount of average power. The high vacuum required for the coming tests of this high power, high frequency klystron with extremely narrow gaps will be produced by the vacuum equipment purchased under this DURIP grant.

The individual 110 kV, 2.7 A klystrons are currently designed for a peak power of 120 kW and an average power of 120 W. An overall efficiency of 34% has been observed in simulation, which is the product of a 55% beam/wave conversion efficiency and 64% circuit efficiency. Ms. Song's research project is to design the rectangular klystron circuit whose dimensions are approximately only 1 mm. The design procedure for the interaction circuit is to design as much as possible with one-dimensional codes and gradually add the finer details of the true 3-D geometry, i.e., first use 1) SLAC's one-dimensional small-signal klystron code, then the 2) one-dimensional large-signal klystron code JAPANDISK, followed by the 3) 2-D MAGIC PIC code, and finally by the 4) 3-D version of MAGIC. The codes MAFIA, HFSS, and SUPERFISH are used to model the electromagnetic circuit. Liqun finished transforming the 3-D MAFIA design model into an equivalent 2-D MAGIC template. The interaction in the output section is simulated with MAGIC2D by injecting a realistic pre-bunched beam. For the case of a simple reentrant cavity, she obtained an efficiency of 35%. Ms. Song completed the design of the extended-interaction output section that employs three coupled cavities and has cold-tested it in a scaled (×10) X-band mock-up. The values for Q_{ext} from measurement and the 3-D MAFIA simulation agree well with each other.

A prototype of three coupled output cavities and one penultimate cavity at 91.4GHz on one substrate has been fabricated on a 60 mm x 60 mm mask using LiGA by SRRC (Synchrotron Radiation Research Center in Taiwan). Three single reentrant cavities at 91.4GHz and two reentrant cavities at 94.0 GHz have been fabricated by EDM. These W-band cavities are ready for test. The purpose of this experiment is to check the dimensional accuracy and quality factor (Q_0)of EDM and LiGA cavities at millimeter wavelength. With the newly released 2-D MAGIC version, we are now able to obtain stable PPM-focused beam simulations using a new laminar beam feature. This was not possible with the old version of MAGIC. A 75 MW X-band klystron at 11.424GHz has been simulated completely. The purposes of this step are 1) to obtain experience in simulating realistic, long klystrons with MAGIC and 2) to test whether the new MAGIC functions compare correctly with the available 75 MW X-band klystron test data. The simulation results of the 75 MW klystron have been successful and presented at the 1999 Particle Accelerator Conference and the ICOP'99 MAGIC Users Group Meeting.

Mr. Li's research project is to develop the electron gun, PPM-focusing, and collector for the modular klystron by using the deformable mesh, electron beam code DEMEOS. Using a 3.0 kG PPM guiding field, Jeff has achieved the transmission of the 110 kV, 2.7 A beam with a 0.25 mm radius through the 0.40 mm radius beam tunnel. For the cathode radius of 0.23 cm, the emission current density is 15 A/cm^2 and the area compression ratio is 87:1. Since the 140 MW/cm^2 power density and 1.3 kA/cm^2 current density of the beam are extremely high, advanced cooling techniques and precise alignment will be required. Based on Jeff's design, a cathode assembly has been ordered from Spectra-Mat for driving the 94 GHz klystron.

The W-Band Modular Klystron project has been advanced by the equipment obtained under the DURIP grant. The DURIP grant allowed us to fabricate a) test cavities for the modular klystron and to purchase b) precision positioning stages for the cavity cold tests, c) the electron gun's cathode assembly from Spectra-Mat, d) an ultra high vacuum mini gate valve from VAT for the beam tunnel to allow the electron gun to remain under vacuum when the circuit is being reconfigured, and e) a Vacion pumping station for the future W-band klystron experiment, where an ultra high vacuum will be needed to avoid RF breakdown in the extremely narrow klystron gaps.

2.4 High Harmonic Gyrotrons

We have received the two novel Cusp electron guns that were ordered from Northrop Grumman under this DURIP grant. A photograph of one is shown in Fig. 1. The thin fluorescent image in Fig. 2 of the axis-encircling electron beam as it impacts a Cerium glass collector shows that the beam has minimal scalloping and indicates that the state-of-the-art design parameters in Table I have probably been satisfied.

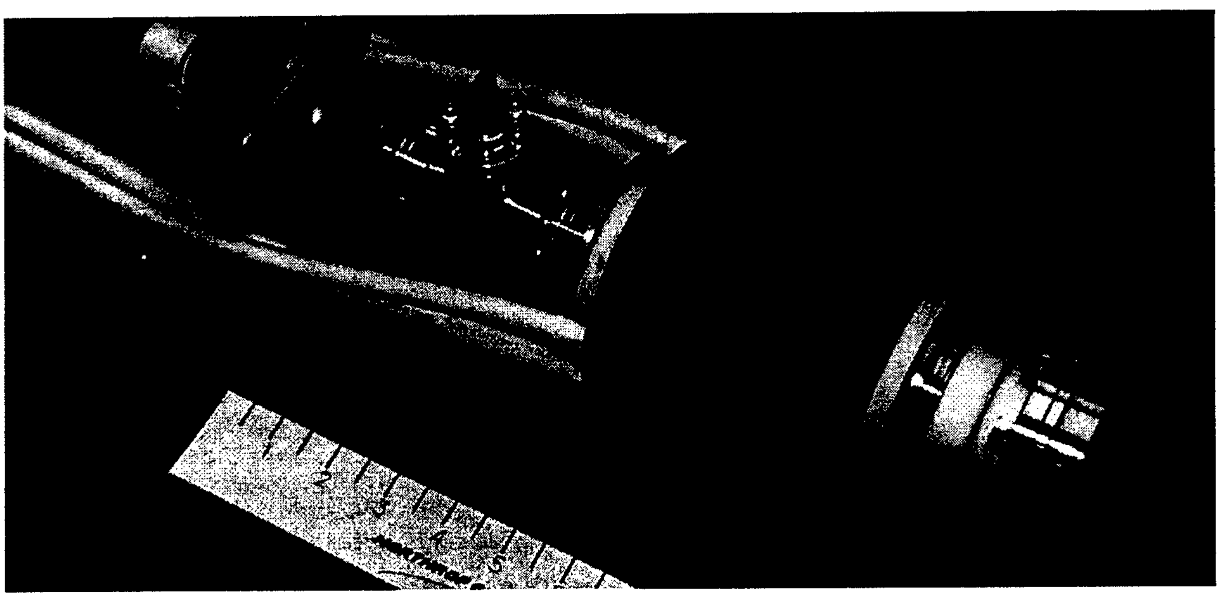

Fig. 1. Photograph of Northrop Grumman Cusp electron gun.

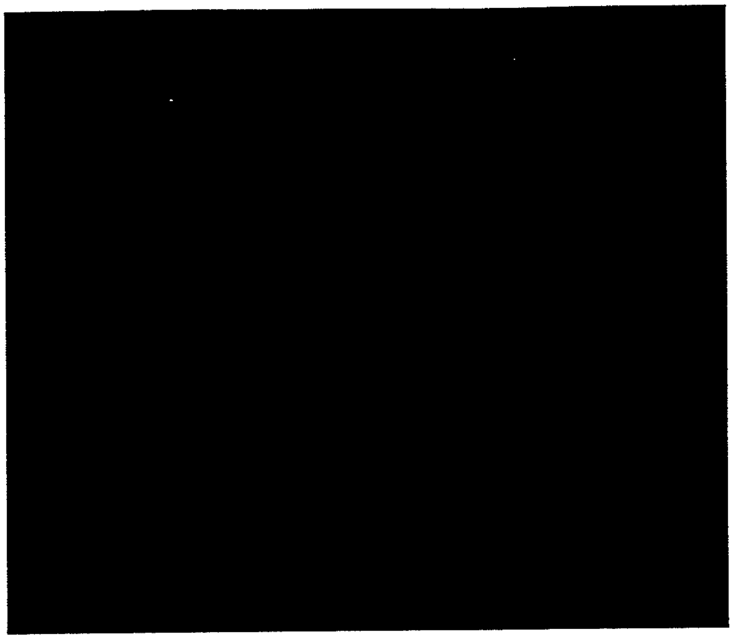

Fig. 2. Fluorescent image of axis-encircling electron beam after it has impacted with a Cerium glass collector.

Table I Parameters of the Northrop Grumman Cusp electron gun for W-band high-harmonic gyrotrons.

Voltage	70 kV
Current	3.5 A
$\alpha = v_{\perp}/v_z$	2.0
$\Delta v_z/v_z$	10%
Beam Ripple, $\Delta r_c/r_c$	10%
Focus Electrode Voltage	71 kV
Cathode Loading, J_c	6.0 A/cm^2
Circuit Magnetic Field, B_o	6.5 kG

These novel electron will produce the axis-encircling electron beams needed by our high harmonic gyrotrons and peniotrons. Our fourth harmonic gyrotron design is predicted to produce an output power level of 75 kW with a device efficiency of 30% and the eighth-harmonic gyrotron design is predicted to produce 20 kW with a depressed collector device efficiency of 20%. The eighth-harmonic device is especially important because it would allow the needed magnetic field to be produced by a lightweight 20 lb permanent magnet. The Cusp guns will also be employed in tests of our second-harmonic peniotron, which is predicted to yield a device efficiency of 50%.

We have continued the construction of a test-stand to investigate high-harmonic W-band gyrotrons and have successfully tested the high voltage pulse modulator. The first objective of this project is to develop a 50 kW sixth-harmonic gyrotron oscillator. ATRI student Ronald Stutzman is the lead investigator on this project under the direction of Dr. D. McDermott. One problem with high frequency gyrotrons is the requirement of a very strong magnetic field to satisfy the fundamental electron cyclotron resonance condition. In this project, the gyrotron has been designed to operate at the sixth-harmonic, which reduces the required magnetic field by a significant factor of six. This will enable the use of conventional copper electromagnets. However, the pulsed experiment that Mr. Stutzman is constructing will use a conventional low temperature superconducting magnet that has been received and tested. Ronald has constructed the HV modulator and successfully tested it. He is currently generating the AUTOCAD drawings of the circuit for its fabrication.

These fundamental studies are intended to satisfy the AF Phillips Laboratory needs for compact, high average power sources at 94 GHz. The objective of the research is to achieve these advanced performance levels at low voltage and reduced magnetic field so that the device can be both compact and lightweight. This will enable the growth of many other DoD applications, as well as numerous commercial applications, such as millimeter-wave ceramic sintering. This research is being performed in collaboration with industrial and government scientists, who provide manufacturability and systems insight, as well as device physics expertise.

The High Harmonic Gyrotron project has also benefited from the vacuum equipment purchased under the DURIP grant. The equipment purchased included a) rebuilt vacuum pumps and equipment from Duniway Stockroom and new vacuum equipment from Varian Vacuum to serve as the high vacuum Vacion pumping station for the test-stand and b) an ultra high vacuum mini gate valve from VAT to close the beam tunnel when the circuit is brought up to air during upgrade reconfigurations so that the electron gun can remain under vacuum.

2.5 High Vacuum Pulser for Phillips Lab

In addition, we have used the DURIP funds to order a $200k ceramic interface for the Phillips Lab Gemini pulser so that it can be operated in the high vacuum environment that is standard in commercial thermionic microwave tubes. We expect this will solve the RF breakdown problems plaguing the system. In this UCD/Stanford collaboration with the Phillips Laboratory, the new pulser was designed by Glenn Scheitrum and fabricated by Stanford.

3.0 Equipment List

Vendor	Item
Behlke Electronics	Transistor Switch w/cooling fins
Duniway	Supplies
Insulator Seal	Supplies
Kurt Lesker	Load Lock Door for 6" OD Conflat Flange
Micron	Millennia MMW 166
MDC Vacuum	Fabrication
Northrop Grumman	2-Custom Cusp electron Gun
Oakland Valve	Supplies
Ocean Optics	Spectrometer System
Omega Engineering	Supplies
Precision Ceramics	Alumina Shouldered Tubing for Plasma Gun Fabricated
Physical Electronics	Sputter Etching System
Staib Instruments	Auger Spectrometry System with XPS and Imaging capabilities
Stanford Research Systems	Digital Delay Generator
Stanford University	Coaxial Ceramic High Voltage Seal Assembly/Vacuum Chamber and Associated Positioning Stages for Testing of W-Band Modular Klystron
Varian Vacuum	Supplies
VAT	Vat Mini Gate Valve, Ultra High Vacuum
Hiden	Electrostatic Plasma Probe
McAllister	UHV Kelvin Probe System